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Two Computer Programs for Predicting Phosphorus Concentrations in New Reservoirs

Manitoba
Environment and
Workplace Safety
and Health

TWO COMPUTER PROGRAMS FOR PREDICTING PHOSPHORUS CONCENTRATIONS IN NEW RESERVOIRS

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Summary

Two computer programs for predicting total phosphorus concentrations in new reservoirs were developed using a published model. Both are written in Basic and are presented in detail. The first program represents a single reservoir and is useful for studying the sensitivity of the model equation to its input parameters. The second program was designed to represent three reservoirs in series, filling simultaneously or consecutively. Each program's limitations, assumptions, and conceptual problems are discussed using Southern Indian Lake, Notigi, and the proposed Wuskwatim reservoirs as examples. The programs are useful for predicting the severity and duration of trophic upsurge due to phosphorus released from flooded land.

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1.0 INTRODUCTION

Phosphorus is considered the controlling nutrient for lake productivity in Canadian Shield lakes (Schindler et al. 1971). Lake phosphorus concentrations can theoretically be calculated by considering P input, output, and sedimentation (Vollenweider 1975). Once lake P concentration is calculated, a prediction of lake productivity can be made. For example, summer chlorophyll a concentrations can be predicted from spring total P concentrations (Dillon and Rigler 1974).

Prediction of P concentrations in reservoirs, as opposed to lakes, must consider additional factors such as reservoir filling rates and the release of P from newly flooded shores. Trophic upsurge in a reservoir, caused by the release of nutrients from flooded land, and the following trophic depression when the additional nutrients are exhausted, were modelled by Ostrofsky and Duthie (1978). They incorporated a time-dependent expression for the leaching of P into the mass balance equation for predicting lake P (Dillon 1974), which itself was a modification of an earlier Vollenweider model. Grimard and Jones (1982) followed the suggestion of Ostrofsky (1978) and modified the reservoir model to include reservoir filling. Other reservoir models that include P prediction are being developed (Thérien and Morrision 1985; de Broissia et al. 1981), but the model of Grimard and Jones (1982) was used here because of its simplicity and general applicability to northern reservoirs.

In this report two P predicting programs, written in Basic, are presented in detail. The first program represents a single reservoir and was designed for studying the sensitivity of the model equation to its input parameters. For example, the effects on predicted P of faster or slower reservoir filling or reducing the available P through harvesting trees are discussed. The second program was designed to represent three reservoirs in series. This program is flexible and can be used to study reservoirs of different volumes, P loading, or area flooded, with impoundment starting simultaneously or consecutively. Both programs are useful for predicting the severity and duration of trophic upsurge due to P released from flooded land.

2.0 THE PROGRAMS

Complete listings of the two programs are given in Appendix 1 (single reservoir) and Appendix 2 (three reservoir system). Both were written in Basic on an IBM personal computer. The model equation used in the programs is equation 12 from Grimard and Jones (1982). The equation is as follows:

$$V[P_w]_t = \frac{M(1-e^{-\phi t})}{\phi} + \frac{a\beta}{\alpha-a}\left(\frac{e^{-at} - e^{-\phi t}}{\phi - a} + \frac{e^{-\phi t} - e^{-\alpha t}}{\phi - a}\right) + V[P_w]_o \cdot e^{-\phi t},$$

$$\text{for } a \neq \phi \neq \alpha,$$

where

V = the reservoir volume in m^3,

$[P_w]_t$ = the P concentration in the reservoir at time t after impoundment, in $mg \cdot m^{-3}$ ($\mu g \cdot L^{-1}$),

M = the annual total P loading of the lake in $mg \cdot yr^{-1}$,

ϕ = the sum of the sedimentation rate coefficient and the flushing rate coefficient ($\sigma + \rho$) in yr^{-1},

a = the flooding coefficient in yr^{-1},

β = the product of the leaching rate coefficient and the total P available in the flooded land, in $mg \cdot yr^{-1}$,

α = the leaching rate coefficient in yr^{-1}, and

$[P_w]_o$ = the calculated steady-state P concentration ($\mu g \cdot L^{-1}$) in a hypothetical lake having the same morphological and hydrological characteristics as the reservoir.

In the single reservoir program (Appendix 1) values for reservoir volume, P loading, etc. are entered in response to prompting from program lines 100 to 160. The time interval for program output (10 or 20 years at 0.5 or 1 year intervals) is chosen in response to line 180. Next, factors for sensitivity analysis are entered in response to line 250, and the variable to be multiplied by the entered factors is chosen (line 310). Phosphorus concentrations (PCALC) are calculated in lines 470 to 510 after the inequality of a, ϕ, and α is tested (to avoid division by zero, line 450). PCALC(2*I,J) is used instead of PCALC(I,J) because the computer will not accept, for example, PCALC(0.5,1) when the time increment chosen for output is 0.5 years. The output section of the program is from line 590 to 760.

A sample screen output from the program is also provided in Appendix 1. Smallwood Reservoir data as given in Grimard and Jones (1982) were used as example data in the program and were used for the sample output. In the example output the filling rate, a, (parameter 4) was multiplied by 0.1, 0.5, 1, 2, and 10. (Note: as a is increased the equation of Grimard and Jones (1982) reduces to the equation of Ostrofsky and Duthie (1978), which does not consider filling rate.

Predicted P peaks at about 23 $\mu g \cdot L^{-1}$ using Smallwood data and the Ostrofsky and Duthie equation (i.e. a >= 10, Appendix 1). This contrasts with the predicted peak of about 130 $\mu g \cdot L^{-1}$ P shown in Figure 2 of Grimard and Jones (1982) for approximately the same data. An error in their Figure 2 is suspected; the earlier model does not overpredict P as extensively as implied by Grimard and Jones.) Option 3 was used for the time interval (10 years, 1 year increments). The program can be re-run if desired (line 770). When the operator quits the program the output can be plotted using a plotting program (i.e. NWA STATPAK 1984): the data were stored in file "P.dat".

The three reservoir program (Appendix 2) was designed to represent reservoirs in series such as those on rivers or involved in diversion schemes (i.e. the Churchill, Burntwood, and Nelson rivers in Manitoba; James Bay hydroelectric development in Quebec). Three sets of variables are entered in response to prompting from lines 60 to 120. The year each reservoir is to start filling is entered in response to line 130. The P calculations for the first reservoir are the same as those in the previous program. Line 250 avoids calculating P (subroutine starting at line 910) if the impoundment has not begun: PCALC is assigned the value of P-initial that was entered in response to line 120.

Phosphorus concentrations for reservoir 2 are calculated in lines 300 to 420. If the inflowing P concentration from reservoir 1 is -99 the P concentration in reservoir 2 is also assigned the value -99 (line 310). The P concentration in reservoir 2 is increased by the same proportion it increased in reservoir 1 (ZZZ, line 330) if

reservoir 2 has not yet been impounded (line 350), because of increased P loading into the reservoir.

After reservoir 2 has been impounded both P loading and P-initial2, used in the PCALC subroutine, are multiplied by the proportion ZZZ (lines 380 and 390). Three assumptions are made. It is assumed that other sources of P, in addition to river supply (i.e. the P concentration in reservoir 1), are insignificant. In riverine systems, perhaps 90% of loading comes from upstream (see Southern Indian Lake calculations below), so this may not be an incorrect assumption. It is also assumed that there is no P sedimentation between reservoirs, a reasonable assumption if the reservoirs are close together. Alternatively, factor ZZZ could be multiplied by a fraction that accounts for additional P sources and sedimentation sinks if either of these two assumptions are considered wrong. Because they act in opposite directions, ignoring both P sedimentation and additional P sources is probably reasonable. The third assumption is that both P loading and P-initial2 increase by the same proportion. As will be seen later this is a necessary assumption if ϕ remains constant (see Section 3.0).

Phosphorus calculations for reservoir 3 (lines 440 to 540) are the same as for reservoir 2. The calculations for the three reservoirs could be placed in one large loop, but this would make modifications to the program to suit particular systems more difficult (see Southern Indian Lake, Notigi, and Wuskwatim reservoirs example, Section 4.2). Line 920 in the PCALC subroutine is necessary to take into account reservoir filling starting after year zero. Line 1010 in

the program is a surplus printing subroutine which was useful for program de-bugging.

A sample output is included in Appendix 2, using Notigi reservoir data for all three reservoirs in series. The Notigi data were used as if the Churchill River diversion had not occurred (see below). Each reservoir started filling at T = 0, and each had an initial P concentration of 30 $\mu g \cdot L^{-1}$. The cumulative effects of the reservoirs in series is obvious.

3.0 CALCULATIONS OF MODEL PARAMETERS FOR SOUTHERN INDIAN LAKE, NOTIGI, AND THE PROPOSED WUSKWATIM RESERVOIRS

This section deals with the the calculation of reservoir volume, loading, ϕ, etc. for Southern Indian Lake and Notigi reservoirs, created during hydroelectric development of the Nelson River, and parameter estimation for the proposed Wuskwatim Reservoir below Notigi. These reservoirs are on the Churchill, Rat and Burntwood Rivers in northern Manitoba. Assumptions made in the calculations will be outlined below. In all cases P refers to total P.

3.1 Southern Indian Lake

In 1976 the northern outlet of Southern Indian Lake was dammed and 75% of the Churchill River flow was diverted south into the Nelson River basin (Newbury et al. 1984). Lake level was raised by about 3 m. Post-impoundment volume was 2.3×10^{10} m^3 (Newbury et al. 1984). Total P loading was estimated to be 8.0×10^{11} $mg \cdot yr^{-1}$ for 1972 and 1973 (Cleugh 1974a).

It was difficult to calculate ϕ, the sum of the sedimentation and flushing rate coefficients. The theoretical

steady-state concentration of P in Southern Indian Lake was calculated to be 13 $\mu g \cdot L^{-1}$ (Appendix 3) using the method given in Grimard and Jones (1982). This was about one-half the actual pre-impoundment concentration of P in the lake (about 25 $\mu g \cdot L^{1}$; Cleugh 1975a). Because of this discrepancy, the calculation for ϕ was done by going directly to equation 3 in Grimard and Jones (1982). From this equation ($\phi = M \cdot V^{-1} \cdot [P]_{\infty}^{-1}$), pre-diversion ϕ was calculated as 1.9 yr^{-1} using 25 $\mu g \cdot L^{-1}$ as the steady-state P concentration, compared to 3.6 yr^{-1} if 13 $\mu g \cdot L^{-1}$ was used. (Pre-diversion volume was 1.7×10^{10} m^3; Newbury et al. 1984.) In riverine systems flushing rate is likely the most important component of ϕ. In Southern Indian Lake flushing rate was about 2 yr^{-1} (Newbury et al. 1984) and P retention was low (about 14%; Cleugh 1974a). The 1.9 yr^{-1} value for ϕ, which was close to the flushing rate, was chosen as the better value for ϕ.

Post-diversion ϕ was calculated as 1.4 yr^{-1} using 25 $\mu g \cdot L^{-1}$ as the steady-state P concentration and a post-diversion volume of 2.3×10^{10} m^3 (Newbury et al. 1984). Again, if flushing rate approximates ϕ in riverine systems this is a reasonable estimate of ϕ ($\rho = 1.4$; Newbury et al. 1984). It is assumed here that when the reservoir reaches steady-state the P concentration would be about the same as it was before impoundment (25 $\mu g \cdot L^{-1}$).

The flooding coefficient, a, was calculated to be about 9 yr^{-1}. To estimate a, the Southern Indian Lake filling curve was constructed from lake levels given in Newbury et al. (1984), assuming the area flooded was approximately linear with depth (McCullough

1981). The best fit of the equation $S = Smax\ (1-e^{-at})$ was plotted to this curve (Figure 1). Smax is the surface area flooded at maximum operating volume of the reservoir (414×10^6 m^2) and S is the surface area flooded at time t after impoundment (Grimard and Jones 1982).

Re-calculation of α, the leaching coefficient was not attempted. The value 0.8 yr^{-1} from Grimard and Jones (1982) was used. Likewise the specific P leaching coefficient, K, was assumed to be 1.9 $g \cdot m^{-2}$ (Grimard and Jones 1982). B, the product of the leaching rate coefficient and the total P available in the flooded land, was calculated as: area flooded $(m^2) \cdot \alpha \cdot K = 6.3 \times 10^{11}$ $mg \cdot yr^{-1}$. Southern Indian Lake data used in the P model are summarized in Table 1.

3.2 Notigi Reservoir

Notigi Lake on the Rat River was dammed in 1974, raising the lake level by 15.2 m over three years (Bodaly et al. 1984a). In 1976 most of the Churchill River flow from Southern Indian Lake was diverted down the Rat River and through Notigi Reservoir. Final reservoir volume was about 4.1×10^9 m^3 (Newbury et al. 1984).

Total P supply to Notigi was estimated to be 6.7×10^{11} $mg \cdot yr^{-1}$ after Churchill River diversion. Cleugh (1974b) estimated P loading to be about 1.4 $g \cdot m^{-2} \cdot yr^{-1}$; the area of Notigi Reservoir was about 480×10^6 m^2 (Bodaly et al. 1984a. Note: Notigi areas in Bodaly et al. (1984a) and Newbury et al. (1984) do not agree; values from Bodaly et al (1984a) were used here. About 10% of the P supply was assumed to be from local waters; this is approximately

Figure 1. Filling curve for Southern Indian Lake reservoir. The fitted curve is for the equation $S=Smax(1-e^{-at})$, when $Smax=414\ km^2$ and $a=9$.

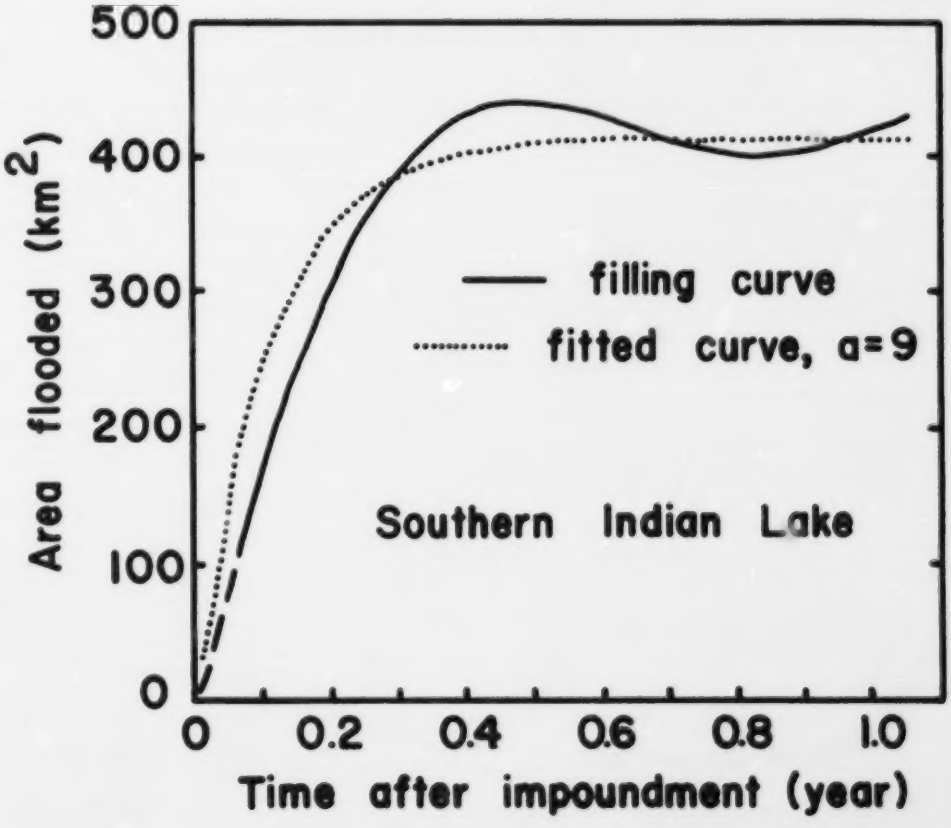


Table 1. Southern Indian Lake data used in the P model.

$V = 2.3 \times 10^{10}\ m^3$
$M = 8 \times 10^{11}\ mg \cdot yr^{-1}$
$\phi = 1.4\ yr^{-1}$
$s = 9\ yr^{-1}$
$\alpha = 0.8\ yr^{-1}$
$\beta = 6.3 \times 10^{11}\ mg \cdot yr^{-1}$
P-initial = $25\ \mu g \cdot L^{-1}$

the difference between estimated P supply (6.7×10^{11} mg·yr^{-1}) and 75% of the P supply (8×10^{11} mg·yr^{-1}) to Southern Indian Lake. The 10% figure is reasonable, because local waters contributed about 10% of P loading to Southern Indian Lake, although Southern Indian Lake has a larger drainage basin than Notigi. In summary, pre-diversion and post-diversion P loadings were estimated to be 7×10^{10} and 7×10^{11} mg·yr^{-1}, respectively.

The calculation of ϕ was done in the same manner as for Southern Indian Lake, with the same assumptions and concerns. The $\phi = M \cdot V^{-1} \cdot [P]_{\infty}^{-1}$ equation was used. Pre-diversion ϕ was 0.6 yr^{-1}, calculated using a steady-state P concentration of 30 µg·L^{-1}, estimated from Cleugh (1974b). Post-diversion ϕ was 6.8 yr^{-1} using 25 µg·L^{-1} as the steady-state P concentration (i.e. assuming that Notigi reservoir would equilibrate to the estimated Southern Indian Lake steady-state P concentration). Flushing rate in the reservoir after diversion was 5.9 yr^{-1} (Newbury et al. 1984). Using 30 µg·L^{-1} as the Notigi steady-state P concentration, post-diversion ϕ is 5.7 yr^{-1}, a little less than the flushing rate. Probably any value of ϕ calculated using Notigi steady-state P concentrations between 25 and 30 µg·L^{-1} would be acceptable.

The flooding coefficient was estimated to be 1 yr^{-1}. A filling curve was made using data from Bodaly et al. (1984a), and the best fit of the equation $S = Smax\ (1-e^{-at})$ was determined, assuming 409×10^6 m^2 were flooded (Bodaly et al. 1984a). β was calculated as 6.2×10^{11} mg·yr^{-1} using the values for α and K given in Grimard and Jones (1982).

Data for Notigi reservoir were also calculated as if the reservoir had been raised by 7.6 m instead of 15.2 m. Reservoir volume was estimated to be 1.7×10^9 m^3. A linear change in area with change in reservoir depth was assumed for the 7.6 m impoundment. The formula $\Delta V = h(A_1 + A_2 + A_1 \cdot A_2) \cdot 3^{-1}$ from Hutchinson (1957) was used to calculate volume. Pre- and post-diversion P loadings were assumed to be unchanged. Pre- and post-diversion ϕ values changed because reservoir volume was different: pre-diversion ϕ was calculated as 1.4 yr^{-1} (assuming steady-state P was 30 $\mu g \cdot L^{-1}$) and post-diversion ϕ was calculated as 16.5 yr^{-1}, assuming steady-state P was 25 $\mu g \cdot L^{-1}$. Post-diversion flushing rate was calculated as 14 yr^{-1}, close to the calculated value of post-diversion ϕ. The flooding coefficient was left as 1 yr^{-1}. β was 3.1×10^{11} $mg \cdot yr^{-1}$ (i.e. 205×10^6 m^2 flooded). Pre- and post-diversion parameter values for Notigi Reservoir raised 15.2 m and 7.6 m are given in Table 2.

3.3 Proposed Wuskwatim Reservoir

Wuskwatim Reservoir is downriver of Notigi Reservoir. The land around the lake was partially flooded by the Churchill River diversion, and will be flooded more if the Wuskwatim dam is constructed for hydroelectric power production. There are a few potential development plans, but the scheme used here (raising the reservoir from 230 m (pre-diversion) to 247 m elevation) is the worst case scenario with respect to land flooding. A summary of the data used in the P model is given in Table 3. Please note that these are very rough estimates.

Table 2. Notigi Reservoir data used in the P model.

Reservoir raised by 15.2 m or 7.6 m.

Pre = pre-diversion; Post = post-diversion.

	15.2m		7.6m	
	Pre	Post	Pre	Post
V (m^3)	4.1×10^9		1.7×10^9	
M ($mg \cdot yr^{-1}$)	7×10^{10}	7×10^{11}	7×10^{10}	7×10^{11}
ϕ (yr^{-1})	0.6	6.8	1.4	16.5
a (yr^{-1})	1		1	
α (yr^{-1})	0.8		0.8	
β ($mg \cdot yr^{-1}$)	6.2×10^{11}		3.1×10^{11}	
P-initial ($\mu g \cdot L^{-1}$)	30		30	

Table 3. Wuskwatim Reservoir data used in the P model. Pre = pre-diversion, Post = post-diversion, and 247m = hypothetical impoundment to 247m.

	Pre	Post	247m
V (m^3)	0.4×10^9	0.7×10^9	3.8×10^9
M ($mg \cdot yr^{-1}$)	1.4×10^{11}	8×10^{11}	8×10^{11}
ϕ (yr^{-1})	10	46	8.4
a (yr^{-1})		1	
α (yr^{-1})		0.8	
β ($mg \cdot yr^{-1}$)	--	8×10^{10}	4×10^{11}
P-initial ($\mu g \cdot L^{-1}$)		35	

Reservoir volumes were estimated using data in Brown (1974) and MacLaren/InterGroup (1984) and the area and volume formula from Hutchinson (1957). Wuskwatim and Notigi drainage basins are of similar size so phosphorus loading to Wuskwatim before the diversion was assumed to be about twice the estimated loading at Notigi before diversion (local P, 7×10^{10} mg$\cdot$yr^{-1}; P flowing from Notigi, 7×10^{10} mg$\cdot$yr^{-1}). Loading after the diversion was estimated by summing local loading plus the P coming from Notigi to yield approximately 8×10^{11} mg$\cdot$yr^{-1}.

The value for ϕ before diversion was 10 yr^{-1}, assuming a steady-state P concentration of about 35 μg$\cdot$L^{-1} (Cleugh 1974b). Pre-diversion flow was about 3.2×10^{9} m$^{3}\cdot$yr^{-1} (Bodaly et al. 1984a). Flushing rate was therefore about 8 yr^{-1}, which is close to the calculated value for ϕ. After the diversion but before hypothetical damming, the value of ϕ for Wuskwatim was 46 yr^{-1}, assuming the steady-state P concentration is 25 μg$\cdot$L^{-1}. Post-diversion flow was about $2\ 8 \times 10^{10}$ m$^{3}\cdot$yr^{-1} (Bodaly et al. 1984a) which yields a flushing rate of about 40 yr^{-1}. Again, flushing rate and calculated ϕ are close: a steady-state P concentration of 28 μg$\cdot$L^{-1} yields ϕ = 41 yr^{-1}, implying that 25-28 μg$\cdot$L^{-1} P are reasonable steady-state assumptions. Reservoir volume would increase after damming and ϕ would decrease to about 8.4 yr^{-1}, using 25 μg$\cdot$L^{-1} P as the steady-state concentration. Flushing rate would be 7.4 yr^{-1}, close to the calculated ϕ value. As an aside, the difference between calculated ϕ and flushing rate increased as flushing rate increased, implying increased sedimentation as flushing rate increases, as reported by

Canfield and Bachmann (1981). They suggested that sedimentation of the larger sediment load accompanying high flushing rates was the mechanism for higher P sedimentation.

The flooding coefficient for Wuskwatim was assumed to be the same as for Notigi (1 yr^{-1}), and α and K were again assumed to be 0.8 yr^{-1} and 1.9 $g \cdot m^{-2}$, respectively. After the diversion, levels immediately below Notigi increased by 2-3 m and approximately 5.5 x 10^7 m^2 were flooded (Bodaly et al. 1984b). Hypothetical damming of Wuskwatim would flood a further 2.6 x 10^8 m^2 (MacLaren/InterGroup 1984). β after diversion was therefore calculated as 8 x 10^{10} $mg \cdot yr^{-1}$, and after damming a further 4 x 10^{11} $mg \cdot yr^{-1}$. An assumption here is that before the Wuskwatim dam was built all the P would leach from land flooded because of the diversion.

4.0 MODEL APPLICATIONS

4.1 Sensitivity Analysis

This exercise was done to test the sensitivity of the model equation to its input parameters. Most of the parameters are inter-related so changing one parameter often results in changes in other parameters. Decreasing planned reservoir volume decreases the area of land flooded and therefore β decreases; ϕ increases because flushing rate increases. Using Notigi data (without Churchill River diversion) a reservoir of one-half the "full" volume shows about one-half the increase in P as the "full" reservoir.

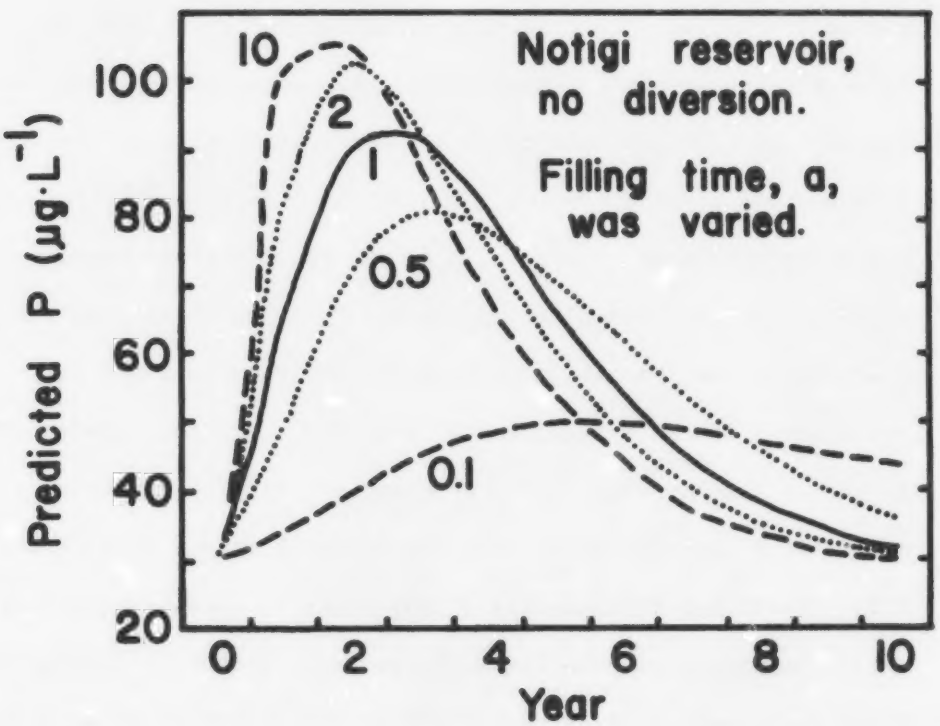
Higher P loading results in a smaller increase in P concentration after flooding if ϕ is varied (i.e. steady-state P

concentration remains the same, therefore flushing rate must increase). This is illustrated with Notigi Reservoir when Churchill River diversion is considered (see Section 4.2). If loading is increased or decreased and other parameters are held constant, then the predicted P concentration in the reservoir changes more or less in proportion to the change in loading. Changing reservoir volume while leaving other parameters constant, also has this effect because, for example, halving reservoir volume is similar to doubling loading.

If ϕ is changed the equilibrium P concentration in the reservoir changes. Increasing ϕ is conceptually the same as increasing reservoir flushing rate: the higher the flushing rate, the smaller the increase in predicted P concentration, and the lower the steady-state P concentration. The faster a reservoir fills (higher a) the higher the peak in predicted P, but the reservoir reaches steady-state conditions faster (Figure 2; Grimard and Jones, 1982). Lowering α, the leaching rate coefficient, reduces β and the predicted P concentrations in the reservoir, but the reservoir takes longer to reach equilibrium. As expected, varying β affects predicted P concentrations in a proportional manner (see Section 4.3). Varying P-initial (the steady-state P concentration) has an effect on predicted P in the early years of reservoir filling but the final P concentration is controlled by the choice of ϕ, as seen earlier.

In general the model is fairly sensitive to all input parameters. Fortunately, reasonable estimates for most variables can be made. The good fit of Notigi and Southern Indian Lake predicted P

Figure 2. Effect of varying reservoir flooding coefficient, a, on predicted P concentrations. Notigi data without Churchill River diversion were used. Values for a were 10, 2, 1, 0.5, and 0.1 yr^{-1}. At year 20 the predicted P concentration of curve a=0.1 is 34 $ug \cdot L^{-1}$.



and observed P concentrations, emphasizes the general applicability of the model.

4.2 Southern Indian Lake, Notigi, and Wuskwatim Reservoirs

Hydroelectric development in northern Manitoba has included the damming of Notigi Lake, which was followed by the diversion of Churchill River water through Notigi from Southern Indian Lake. Wuskwatim was partially flooded by the diversion, and the later, hypothetical damming of Wuskwatim reservoir would flood more land. The three reservoir model (Appendix 2) was modified to reflect this development sequence.

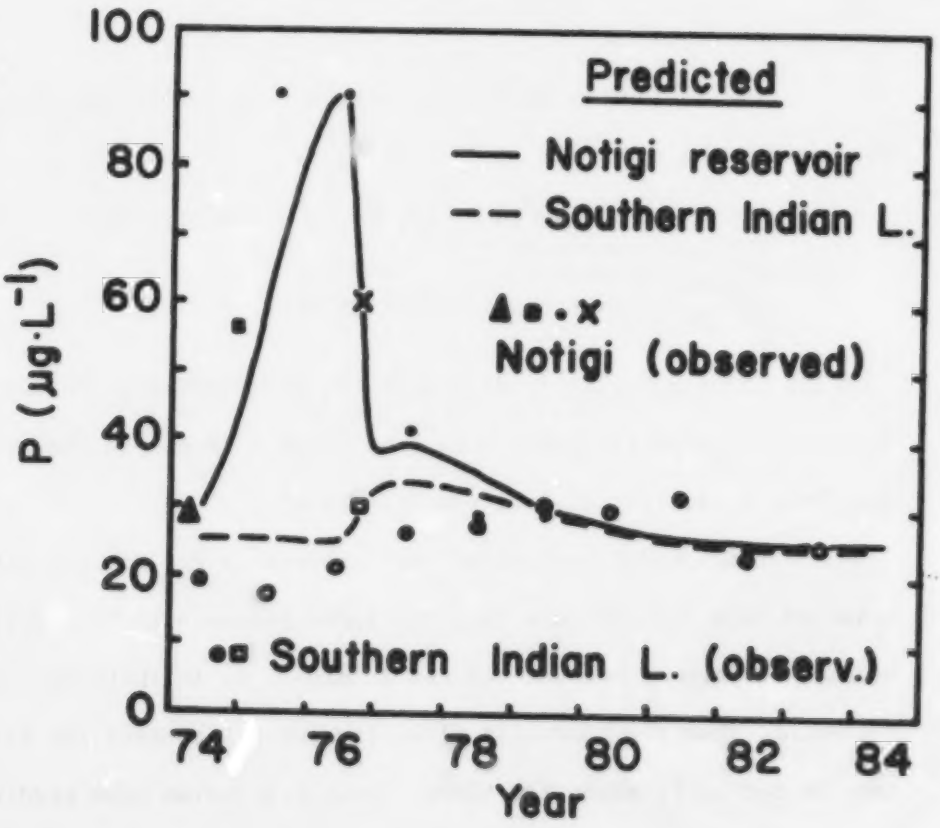
The following modifications were used for Notigi reservoir to account for the diversion at T = 2.5 years.

```
382 REM THE NEXT 3 LINES ARE SPECIFIC FOR S.I.L. AND NOTIGI RESERVOIRS.
383 IF I(2.5 THEN GOTO 390
384 M(J)=M(J)*10:PHI(J)=6.8
385 REM THE PREVIOUS LINE HAS CHANGED P LOADING AND PHI.
```

Line 384 changes Notigi loading and ϕ to post-diversion values. Data entered into the model were from Table 1 (Southern Indian Lake) and Table 2 (Notigi; 15.2 m, pre-diversion).

Predicted P concentrations, especially for Notigi, fit observed data well (Figure 3). The large increase in P in Notigi because of impoundment was reduced in mid-1976, in spite of increased P loading, when the Churchill River diversion increased the flushing rate in Notigi by about ten times. Southern Indian Lake predicted and observed data do not agree as well, partly because the data from near South Indian Lake settlement were not necessarily representative of the whole lake. Before diversion, that section of the lake was

Figure 3: Predicated and observed P concentrations for Southern Indian Lake and Notigi reservoirs. Sources of observed P were: ▲ Cleugh (1974b); ■ Jackson and Hecky (1980); ● R. Hecky, Freshwater Institute (pers. comm.); X and □ , Planas and Hecky (1984); O near South Indian Lake Settlement (Manitoba data).



sheltered and after diversion it was along the main stem of the diversion flow (Newbury et al. 1984).

The following modifications to the three reservoir program were used to account for Wuskwatim flooding due to diversion and subsequent flooding after hypothetical damming at T = 6 years. (T = 6 years was chosen for graphing convenience; any value greater than 5 or 6 would yield similar results.)

```
470 PCALC(2*I,J)=PINIT3*.865+PINIT3*ZZZ*.135
473 REM THE NEXT SECTION WAS MODIFIED FOR NOTIGI AND WUSKWATIM RESERVOIRS.
475 TTTT=T(3)
480 IF I(2.5 THEN GOTO 550
490 REM CALCULATE THE INCREASE IN M AND P-initial USING ZZZ.
495 ZZZ=PCALC(2*I,J-1)/PINIT1
500 M(J)=ZZZ*M3
504 V(J)=7E+08:M(J)=M(J)*5.71:PHI(J)=46
505 REM V3, M3, AND Phi3 HAVE BEEN MODIFIED BECAUSE OF DIVERSION FLOW.
506 IF T(3))I THEN GOTO 510
508 V(J)=3.8E+09:PHI(J)=8.399999:B(J)=4E+11
509 REM V3, Phi3, AND B3 HAVE CHANGED BECAUSE OF WUSKWATIM IMPOUNDMENT.
510 PINIT(J)=ZZZ*PINIT3
515 IF I(T(3) THEN T(3)=2
      -

550 T(3)=TTTT:NEXT I
```

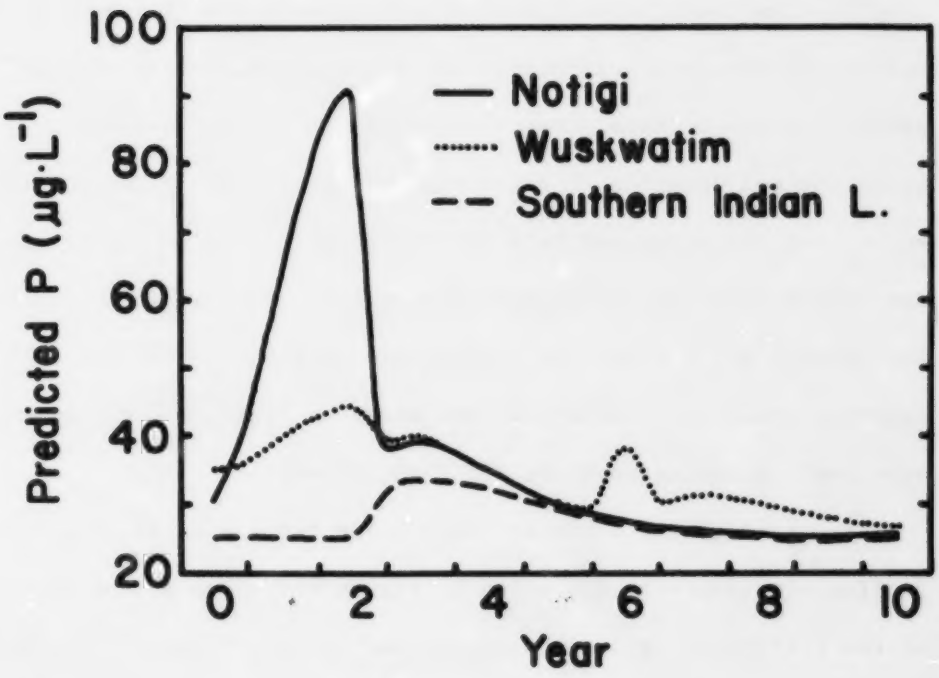
Line 470 calculates the P concentration in Wuskwatim before the diversion (T < 2.5; see line 480). Here, local drainage was not ignored because it contributed about 50% of P loading before Notigi was dammed (local drainage in effect dilutes the increased P coming from upriver). Flow through Notigi was reduced to about 27% of its regular flow during Notigi filling (Inland Waters Directorate, Water Survey of Canada data) so its proportional contribution to Wuskwatim P concentration was 0.5 x 0.27 = 0.135% during filling. Local drainage contributed the rest (0.865%). This calculation was used instead of

re-calculating V, M, and ϕ for reduced flow through Notigi. Line 475 stores the value of T(3), the time Wuskwatim reservoir is impounded, in TTTT (see lines 515 and 550).

If T > 2.5 (after diversion) line 495 re-calculates ZZZ using PINIT1, not PINIT2. Concentrations of all three reservoirs were designed to approach 25 $\mu g \cdot L^{-1}$ (PINIT1). If PINIT2 (30 $\mu g \cdot L^{-1}$) is used in the ZZZ calculation then the Wuskwatim steady-state P concentration is forced below 25 $\mu g \cdot L^{-1}$. Line 500 calculates the proportional increase in Wuskwatim loading, this time ignoring local P contribution (< 10% of total). Post-diversion volume, loading, and ϕ are assigned in line 504. If Wuskwatim has been dammed (T(3) <=I, line 506) then reservoir volume, ϕ, and β are changed (line 508). PINIT3 is increased by the proportion ZZZ (line 510). Line 515 is needed to calculate the P increase due to flooded land after river diversion. Lines 520 - 540 (Appendix 2) were not changed. The correct value of T(3) is restored in line 550. As the program is written, the input parameters must all be entered when the program is re-run, because of the re-assigned values in lines 384, 504, and 508.

Predicted P concentrations for Southern Indian Lake, Notigi, and Wuskwatim reservoirs are given in Figure 4 (computer output is given in Appendix 4). Modelled Wuskwatim P concentrations did not increase as much as in Notigi in the first few years because the flow through Notigi was low and because of dilution by local water. As with Notigi, predicted P decreased after the diversion because flushing rate increased. Phophorus released from flooded land after the diversion was insignificant (about 1 $\mu g \cdot L^{-1}$, year 3). The

Figure 4. Predicted P concentrations for Southern Indian Lake, Notigi, and Wuskwatim reservoirs.



hypothetical, worst-case scenario for Wuskwatim damming at year 6 resulted in a relatively small increase in predicted P concentration, mainly because of the high flushing rate in the reservoir due to the Churchill River diversion. Unfortunately there are no P data from Wuskwatim to test the model predictions. If Wuskwatim is dammed there will probably be data collected before and after impoundment which could be used to test the model predictions.

4.3 Reservoir Planning

The two models presented in this report will likely be most useful for reservoir planning. If reasonable estimates of model parameters can be made, then the models can predict estimates of the magnitude and duration of P upsurge. If a critical P concentration is known then the model can help determine which development scheme will not exceed that concentration. The effects of halving the depth of impoundment and halving the P available in the flooded land (i.e. by removing trees and vegetation) are shown in Figure 5. Notigi data were used, assuming no Churchill River diversion.

Predicted P concentrations below two 7.6 m reservoirs coming on-line consecutively are given in Figure 6. Although the magnitude of the P increase is lower with the two shallower reservoirs, the duration of trophic upsurge is longer. Harvesting the trees in the second reservoir would reduce the second peak in P. Phosphorus concentrations below two 7.6 m reservoirs on-line simultaneously are predicted to be worse than those resulting from a single 15.2 m reservoir (Figure 7). The cumulative effect of the reservoirs was seen earlier (Appendix 2) with three 15.2 Notigi impoundments in series. Harvesting the trees in one reservoir (β divided by 2)

Figure 5. Predicted P concentrations using Notigi Reservoir data, without Churchill River diversion. Full (15.2 m) and 7.6 m impoundments, with harvested or unharvested trees (i.e. β = 3.1 or 6.2×10^{11} mg. yr^{-1}).

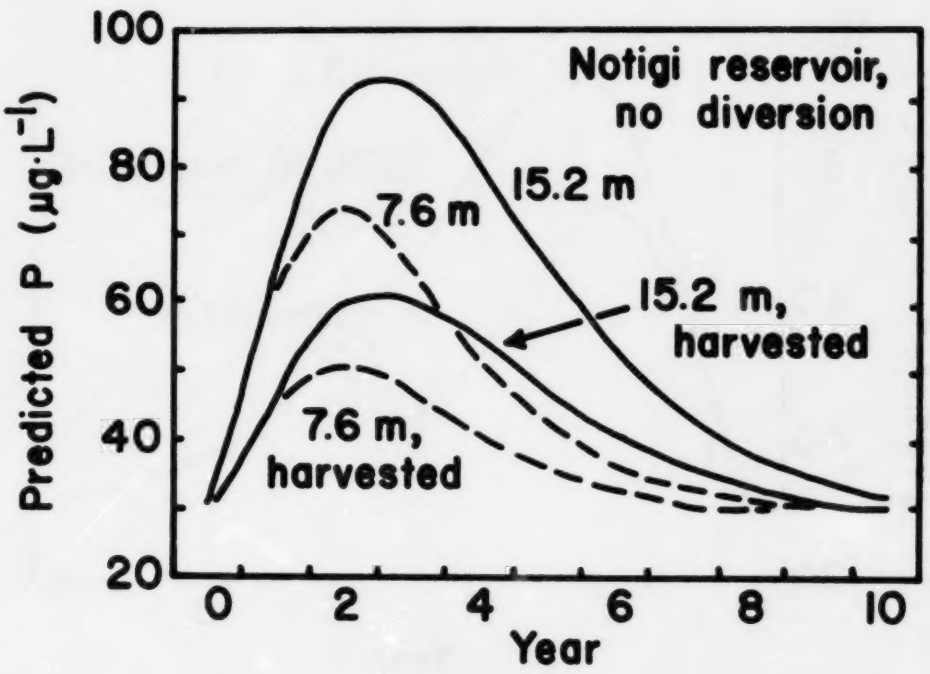


Figure 6. Predicted P concentrations using Notigi Reservoir data, without Churchill River diversion. One 15.2 m impoundment or two consecutive 7.6 m impoundments. The second 7.6 m impoundment has either harvested or unharvested trees (i.e. β = 3.1 or 6.2×10^{11} mg. yr^{-1}).

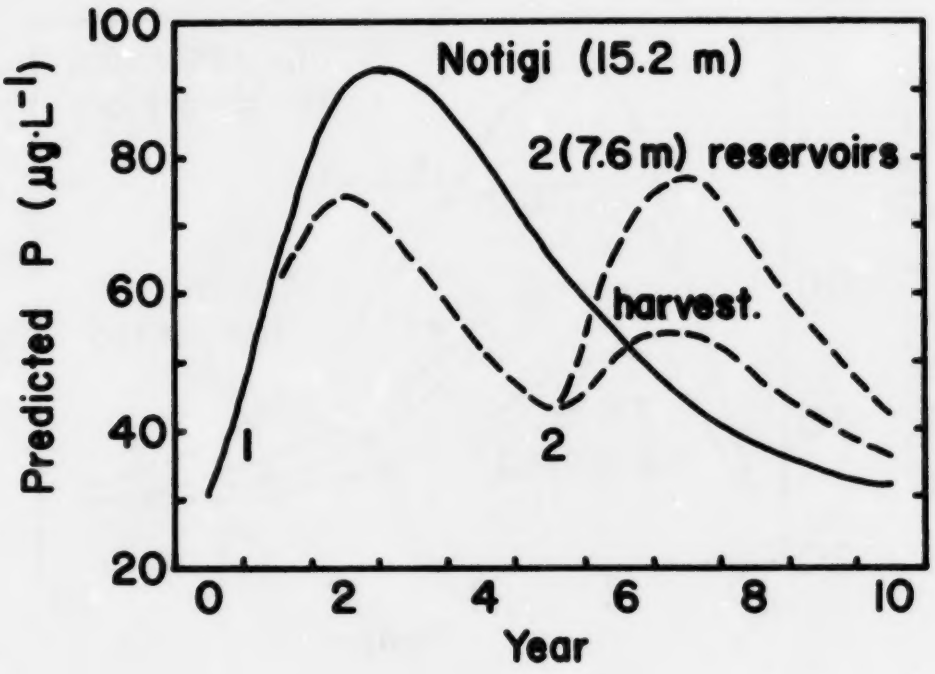
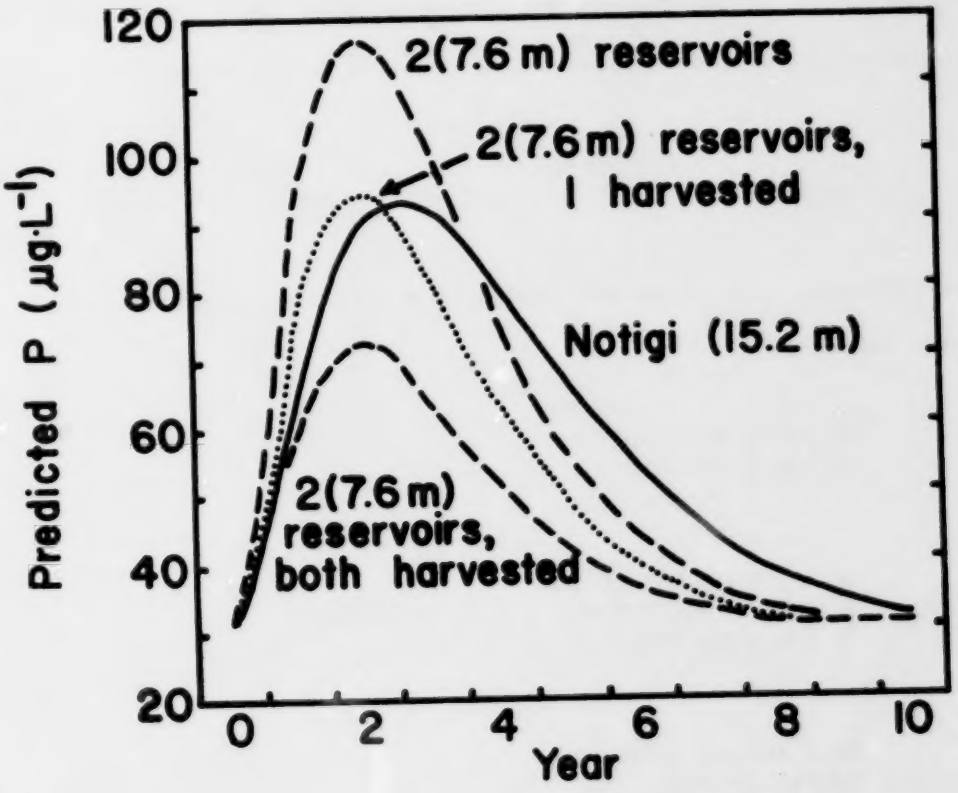


Figure 7. Predicted P concentrations using Notigi Reservoir data, without Churchill River diversion. One 15.2 m impoundment or two simultaneous 7.6 m impoundments, one or both with trees harvested.



makes the two schemes about the same; two 7.6 m reservoirs, both harvested, are predicted to cause even smaller increases in P concentration.

4.4 A Possible Model Modification

It has been suggested that the term $[P_w]_o$ in the equation of Grimard and Jones (1982) be replaced by $[\text{Predicted-P}]_{t-1}$ (D. Roy, Societé Energie de la Baie James, 800 de Maisonneuve E., Montréal, P.Q; pers. comm.). This modification accounts for the P concentration in the reservoir in the preceding year. Modifying the single reservoir model (Appendix 1) requires two program lines.

```
455 IF I=T OR I=INTER THEN GOTO 470
456 PINIT=PCALC(2*(I-1),J)
```

The following nine lines are needed to modify the three reservoir model (Appendix 2).

```
252 IF 2*(I-1)>0 THEN GOTO 254
253 PINIT(J)=PINIT1:GOTO 260
254 PINIT(J)=PCALC(2*(I-1),J)


385 IF 2*(I-1)>0 THEN GOTO 390
386 PINIT(J)=PINIT2:GOTO 400
390 PINIT(J)=PCALC(2*(I-1),J)


502 IF 2*(I-1)>0 THEN GOTO 510
503 PINIT(J)=PINIT3:GOTO 520
510 PINIT(J)=PCALC(2*(I-1),J)
```

This modification to the predictive equation increases slightly the magnitude and duration of the predicted P upsurge (D. Roy, pers. comm.). With this modification and using Notigi data

without diversion predicted P was 10 $\mu g \cdot L^{-1}$ higher at year 2, 12 $\mu g \cdot L^{-1}$ higher at year 3, 7 $\mu g \cdot L^{-1}$ higher at year 4, 3 $\mu g \cdot L^{-1}$ higher at year 5, and 1 $\mu g \cdot L^{-1}$ higher at year 6 than was calculated previously (Appendix 2, sample output, reservoir 1). In riverine systems with high flushing rates it is probably not necessary to consider the previous year's P concentration. The good fit of the predicted and observed Notigi data (Figure 3) supports this. Additional work is required to determine which equation applies to a particular system.

4.5 Future Work

The P predictive model of Grimard and Jones (1982) is versatile and is useful for predicting the magnitude and duration of trophic upsurge due to P released from flooded land. The computer programs presented here should be useful for reservoir planning to help minimize the adverse effects of impoundments. The close fit of the Notigi predicted and observed P concentrations suggests that the estimates of the parameters used in the model were good. The values of the leaching rate coefficient (α) and the specific P leaching coefficient (K) supplied by Grimard and Jones (1982) appear to be reasonable estimates. In riverine systems, flushing rate can approximate ϕ, implying that sedimentation rate is a minor component in rapidly flushed reservoirs.

The simple empirical equation of Dillon and Rigler (1974) predicts summer chlorophyll a concentrations from spring total P concentrations. Dillon and Rigler (1974) suggested that combining their equation with a P predictive model would be useful. However,

models like theirs should be applied cautiously to new reservoirs (Planas and Hecky 1984) because high turbidity in reservoirs may reduce primary productivity through light limitation (Hecky and Guildford 1984; Chow-Fraser and Duthie 1983; Gloss et al. 1980) or by sequestering Fe and other trace metals (Jackson and Hecky 1980). Advection should also be considered in a productivity equation because rapidly flushed reservoirs may have lower than expected chlorophyll concentrations (Søballe and Threlkeld 1985; Uttormark and Hutchins 1985). Equations predicting zooplankton biomass from total P (see Yan 1986) may also need to be modified to include advection and turbidity. Preliminary work suggests that advection, turbidity, and total P can be used to predict riverine lake and reservoir productivity (shown by chlorophyll a). An equation like this could easily be appended to the P predictive model.

It appears that increased concentrations of nutrients in northern reservoirs are responsible for increased methylation of mercury by bacteria, which ultimately results in increased mercury levels in fish (Bodaly et al. 1984b; D. Bodaly and R. Hecky, Fisheries and Oceans, 501 University Crescent, Winnipeg, Manitoba; pers. comm.). Using predicted lake P concentrations as a nutrient analog it may be possible to predict the increase and subsequent decrease of methyl mercury (biologically available Hg) in a reservoir. Fish mercury content would be expected to follow the P curve, likely with a lag period dependent on the species of fish, its diet, and its living habits. The P model of Grimard and Jones (1982) has recently been applied, with reasonable success, to pike and whitefish mercury levels in northern Quebec reservoirs (D. Roy, pers. comm.).

The P predictive models coupled with productivity or fish mercury models could benefit hydroelectric development by helping cost/benefit analysis while the projects are still in the planning stage. The models can provide rough predictions of environmental effects of different development scenarios and, if needed, compensation could be worked out before the overall best development scheme is started. For example, a quickly-filled reservoir may result in high productivity and high mercury levels in fish but for a relatively short time period, during which fishing could be banned. Slower reservoir filling might result in less drastic increases in productivity and fish mercury, which could allow a limited fishery, but elevated mercury levels in fish would persist longer. If monetary, engineering, and environmental factors are considered at the outset then the adversarial nature of development, money vs. environment, can be reduced.

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APPENDIX 1

SINGLE RESERVOIR COMPUTER PROGRAM

Appendix 1. Single reservoir program.

```
10 REM MODEL TO CALCULATE PHOSPHORUS CONCENTRATION IN A RESERVOIR.  AFTER GRIMARD AND JONES (1982).
20 REM EXAMPLE DATA ARE FROM SMALLWOOD RESERVOIR.  R. PLAYLE 1986.
30 DIM PCALC(100,100),F(10)
40 V=0:M=0:PHI=0:A=0:B=0:ALPHA=0:PINIT=0
50 T=0:TT=0:INTER=0:EPHIT=0:G=0
60 CLS:PRINT:PRINT:PRINT"          Model to calculate P concentrations in a reservoir    ":PRINT:PRINT:PRINT
70 LL=0:MM=0:NN=0:ZZ=0:PCALC=0:VV=0:PP=0:PRINT:PRINT:PRINT:PRINT"                          *  Input data  *  "
80 REM INPUT DATA, TIME INTERVALS FOR THE MODEL, AND FACTORS FOR SENSITIVITY ANALYSIS.
90 PRINT:PRINT
100 INPUT "Input V, the reservoir volume in m cubed.  e.g. 8.4E10 ";V:PRINT
110 INPUT "Input M, the annual total P loading to the reservoir in mg/yr.                    e.g. 6.8E11 ";M:PRINT
120 INPUT "Input Phi, the sum of the sedimentation rate coefficient and the flushing rate          coefficient (sigma + rho) in /yr.  e.g. 1.35 ";PHI:PRINT
130 INPUT "Input a, the flooding coefficient in /yr.  e.g. 1.0 ";A:PRINT
140 INPUT "Input Alpha, the leaching rate coefficient, in /yr.  e.g. 0.82 ";     ALPHA:PRINT
150 INPUT"Input B, the product of the leaching rate coefficient and the total P available          in the flooded land, in mg/yr.  e.g. 4.2E12 ";B:PRINT
160 INPUT "Input P-initial, the concentration of P in the reservoir at or before                  impoundment (i.e. at t=0), in ug/L.  e.g. 6.0 ";PINIT:PRINT
170 V1=V:M1=M:PHI1=PHI:A1=A:ALPHA1=ALPHA:B1=B:PINIT1=PINIT
180 INPUT"What time intervals do you want?              1.  t=0 to 20, 1 yr increments.        2.  t=0 to 20, 0.5 yr increments.       3.  t=0 to 10, 1 yr
          increments.         4.  t=0 to 10, 0.5 yr increments.       Enter 1, 2, 3, or 4.  e.g. 3 ";ZZ:PRINT
190 ON ZZ GOSUB 200,210,220,230:GOTO 250
200 T=0:TT=20:INTER=1:RETURN
210 T=0:TT=20:INTER=.5:RETURN
220 T=0:TT=10:INTER=1:RETURN
230 T=0:TT=10:INTER=.5:RETURN
240 PRINT
250 INPUT"Input factors you wish to multiply a variable by.  Five are required.  e.g. 0.1, 0.5, 1, 2, and 10.  Enter one at a time and hit 'RETURN'.  ";F(1)
260 INPUT;F(2):PRINT
270 INPUT;F(3):PRINT
280 INPUT;F(4):PRINT
290 INPUT;F(5):PRINT
300 PRINT
310 INPUT "Which variable do you wish to see multiplied by the chosen factors?                1. V   2. M   3. Phi   4. a   5. Alpha   6. B
             7. P-initial        Enter 1 or 2, etc. ";VV:PRINT
```

```
320 CLS:PRINT:PRINT:PRINT:PRINT:PRINT:PRINT:PRINT:PRINT"                    *    WORKING    *"
330 FOR I=T TO TT STEP INTER
340 FOR J=1 TO 5
350 REM SENSITIVITY ANALYSIS SECTION.
360 ON VV GOSUB 380,390,400,410,420,430,440
370 GOTO 450
380 V=V1*F(J):RETURN
390 M=M1*F(J):RETURN
400 PHI=PHI1*F(J):RETURN
410 A=A1*F(J):RETURN
420 ALPHA=ALPHA1*F(J):RETURN
430 B=B1*F(J):RETURN
440 PINIT=PINIT1*F(J):RETURN
450 IF A=PHI OR PHI=ALPHA OR A=ALPHA THEN GOTO 530
460 REM CALCULATION SECTION.
470 EPHIT=EXP(-PHI*I)
480 LL=(A*B)/(ALPHA-A)
490 MM=(EXP(-A*I)-EPHIT)/(PHI-A)
500 NN= (EPHIT-EXP(-ALPHA*I))/(PHI-ALPHA)
510 PCALC(2*I,J)= ((M/PHI)*(1-EPHIT)+LL*(MM+NN)+V*PINIT*EPHIT)/V
520 GOTO 550
530 PCALC(2*I,J)=-99
540 PRINT
550 V=V1:M=M1:PHI=PHI1:A=A1:ALPHA=ALPHA1:B=B1:PINIT=PINIT1
560 NEXT J
570 NEXT I
580 REM OUTPUT SECTION.
590 OPEN "P.DAT" FOR OUTPUT AS #1
600 CLS:PRINT:PRINT:PRINT"   Parameter";VV;"was varied by factors";F(1);",";F(2);",";F(3);",";F(4);", and";F(5);"."
610 PRINT:PRINT"Year      Pcalc(";F(1);")   Pcalc(";F(2);")   Pcalc(";F(3);")   Pcalc(";F(4);")   Pcalc(";F(5);")"
620 PRINT"-------------------------------------------------------------------------"
630 PRINT
640 FOR I=T TO TT STEP INTER
650 PRINT I TAB(8)
660 PRINT #1,USING "##.#";I;
670 FOR J=1 TO 5
```

```
680 PRINT USING "$$$$$$$$$.$$$";PCALC(2*I,J);
690 PRINT #1,USING"$$$$.$$$";PCALC(2*I,J);
700 NEXT J
710 PRINT:PRINT #1," "
720 NEXT I
730 PRINT"_____"
740 PRINT:PRINT "V =";V;"    M =";M;"    PHI =";PHI;"    A =";A
750 PRINT "ALPHA =";ALPHA;"    B =";B;"    P-initial =";PINIT;"         Parameter varied:";VV:PRINT
760 CLOSE #1
762 INPUT"Press any numeric key to continue.    ";PP
764 IF PP()-99 THEN GOTO 766
766 PRINT
770 INPUT "1.  Enter new variables?  2.  Do you want to change the multiplication factors?3.  Do you want to pick another variable to multiply by the
          present factors?   4.  Quit.  Enter 1, 2, 3, or 4.";PP
780 IF PP=1 THEN GOTO 40
790 IF PP=2 THEN GOTO 240
800 IF PP=3 THEN GOTO 300
810 PRINT:PRINT"                                    *  DONE  *  "
820 PRINT:PRINT"          Enter 'SYSTEM' to use STATPAK package.  File name is 'P.dat'."
830 END
```

Sample output, using example data in program.

Parameter 4 was varied by factors .1 , .5 , 1 , 2 , and 10 .

Year	Pcalc(.1)	Pcalc(.5)	Pcalc(1)	Pcalc(2)	Pcalc(10)
0	6.000	6.000	6.000	6.000	6.000
1	7.210	11.209	14.740	18.815	22.986
2	8.511	14.945	18.369	19.893	18.602
3	9.124	14.878	15.956	14.923	12.876
4	9.262	13.139	12.399	10.746	9.371
5	9.158	11.163	9.650	8.312	7.572
6	8.952	9.513	7.937	7.076	6.713
7	8.714	8.302	6.979	6.488	6.318
8	8.474	7.472	6.478	6.217	6.140
9	8.247	6.926	6.227	6.095	6.060
10	8.037	6.575	6.105	6.040	6.025

V = 8.4E+10 M = 6.8E+11 PHI = 1.35 A = 1
ALPHA = .82 B = 4.2E+12 P-initial = 6 Parameter varied: 4

Press any numeric key to continue. ?

APPENDIX 2

THREE RESERVOIRS COMPUTER PROGRAM

Appendix 2. Three reservoir program.

```
10 REM    MODEL TO CALCULATE P IN A SERIES OF FILLING RESERVOIRS
20 REM    R. PLAYLE 1986.  MODIFIED FROM GRIMARD AND JONES (1982)
30 DIM PCALC(100,100),V(5),M(5),PHI(5),A(5),ALPHA(5),PINIT(5),B(5),T(5)
40 CLS:PRINT:PRINT:PRINT:PRINT"       Model to calculate P concentrations in a three-reservoir series"
50 PRINT:PRINT:PRINT:PRINT:PRINT"                          *   Input data   *":PRINT:PRINT
60 INPUT"Input V1, V2, V3.  e.g. 8.4E10";V(1):INPUT;V(2):INPUT;V(3):PRINT
70 INPUT"Input M1, M2, M3.  e.g. 6.8E11";M1:INPUT;M2:INPUT;M3:PRINT
80 INPUT"Input Phi1, Phi2, Phi3.  e.g. 1.35";PHI(1):INPUT;PHI(2):INPUT;PHI(3):PRINT
90 INPUT"Input a1, a2, a3.  e.g. 1.0";A(1):INPUT;A(2):INPUT;A(3):PRINT
100 INPUT"Input Alpha1, Alpha2, Alpha3.  e.g. 0.82";ALPHA(1):INPUT;ALPHA(2):INPUT;ALPHA(3):PRINT
110 INPUT"Input B1, B2, B3.  e.g. 4.2E12";B(1):INPUT;B(2):INPUT;B(3):PRINT
120 INPUT"Input P-initial1, P-initial2, P-initial3.  e.g. 6";PINIT1:INPUT;PINIT2:INPUT;PINIT3:PRINT
130 INPUT"Input T1, T2, T3, the year you want each reservoir to start filling.                Enter 0 to 20 for each.  ";T(1):INPUT;T(2):INPUT;T(3):PRINT
140 INPUT"What time intervals do you want?              1.  t=0 to 20, 1 yr increments.       2.  t=0 to 20, 0.5 yr increments.       3.  t=0 to 10,
                1 yr increments.       4.  t=0 to 10, 0.5 yr increments.       Enter 1, 2, 3, or 4. ";ZZ:PRINT
150 ON ZZ GOSUB 160,170,180,190:GOTO 200
160 T=0:TT=20:INTER=1:RETURN
170 T=0:TT=20:INTER=.5:RETURN
180 T=0:TT=10:INTER=1:RETURN
190 T=0:TT=10:INTER=.5:RETURN
200 CLS:PRINT:PRINT:PRINT:PRINT:PRINT:PRINT"                              *   WORKING   *"
210 FOR I=T TO TT STEP INTER
220 REM RESERVOIR 1 CALCULATIONS.
230 J=1
240 PINIT(J)=PINIT1:M(J)=M1
250 IF T(1)>I THEN GOTO 280
260 GOSUB 910
270 GOTO 300
280 PCALC(2*I,J)=PINIT1
290 REM RESERVOIR 2 CALCULATIONS.
300 J=J+1
```

```
310 IF PCALC(2*I,J-1)=-99 THEN GOTO 420
320 REM CALCULATE ZZZ, THE PROPORTIONAL INCREASE IN M AND P-initial.
330 ZZZ=PCALC(2*I,J-1)/PINIT1
340 PCALC(2*I,J)=PINIT2*ZZZ
350 IF T(2)>I THEN GOTO 440
360 REM CALCULATE THE INCRESE IN LOADING (M) AND P-initial USING ZZZ.
370 REM OTHER SOURCES OF P BESIDES RIVER SUPPLY ARE CONSIDERED INSIGNIFICANT.
380 M(J)=ZZZ*M2
390 PINIT(J)=ZZZ*PINIT2
400 GOSUB 910
410 GOTO 440
420 PCALC(2*I,J)=-99
430 REM RESERVOIR 3 CALCULATIONS.
440 J=J+1
450 IF PCALC(2*I,J-1)=-99 THEN GOTO 540
460 ZZZ=PCALC(2*I,J-1)/PINIT2
470 PCALC(2*I,J)=PINIT3*ZZZ
480 IF T(3)>I THEN GOTO 550
490 REM CALCULATE THE INCREASE IN M AND P-initial USING ZZZ.
500 M(J)=ZZZ*M3
510 PINIT(J)=ZZZ*PINIT3
520 GOSUB 910
530 GOTO 550
540 PCALC(2*I,J)=-99
550 NEXT I
560 OPEN "P.DAT"FOR OUTPUT AS #1
570 CLS:PRINT:PRINT:PRINT:PRINT"Reservoir:      1           2           3"
580 PRINT"_____":PRINT
590 PRINT"        V:    ";V(1);"    ";V(2);"    ";V(3)
600 PRINT"        M:    ";M1;"    ";M2;"    ";M3
610 PRINT"      Phi:    ";PHI(1);"       ";PHI(2);"       ";PHI(3)
620 PRINT"        a:    ";A(1);"          ";A(2);"          ";A(3)
630 PRINT"    Alpha:     ";ALPHA(1);"        ";ALPHA(2);"        ";ALPHA(3)
640 PRINT"        B:    ";B(1);"    ";B(2);"    ";B(3)
650 PRINT"        T:    ";T(1);"          ";T(2);"          ";T(3)
660 PRINT:PRINT:PRINT"Year         PCALC(1)     PCALC(2)     PCALC(3)"
```

```
670 PRINT"_____":PRINT
680 FOR I=T TO TT STEP INTER
690 PRINT I TAB(8)
700 PRINT #1, USING "##.#";I;
710 FOR J=1 TO 3
720 PRINT USING "##########.###";PCALC(2*I,J);
730 PRINT #1, USING "##########.###";PCALC(2*I,J);
740 NEXT J
750 PRINT:PRINT #1," "
760 NEXT I
770 PRINT"_____":PRINT
780 CLOSE #1
790 INPUT"Press any numeric key to continue.  ";PP
800 IF PP()-99 THEN GOTO 810
810 PRINT
820 INPUT"1.  Enter all new variables?     2.  Do you want to change variables starting  from A?      3.  Do you want to change only P-initial and the
                        time interval?  4.  Quit.    Enter 1, 2, 3, or 4.  ";PP
830 CLS:PRINT:PRINT:PRINT:PRINT
840 IF PP=1 THEN GOTO 60
850 IF PP=2 THEN GOTO 90
860 IF PP=3 THEN GOTO 120
870 PRINT:PRINT"                                  *   DONE   *"
880 PRINT:PRINT"        Enter 'SYSTEM' to use STATPAK package.  File name is 'P.Dat'."
890 END
900 REM PCALC SUBROUTINE
910 IF A(J)=PHI(J) OR PHI(J)=ALPHA(J) OR A(J)=ALPHA(J) THEN GOTO 990
920 X=I-T(J)
930 EPHIT=EXP(-PHI(J)*X)
940 LL=(A(J)*B(J))/(ALPHA(J)-A(J))
950 MM=(EXP(-A(J)*X)-EPHIT)/(PHI(J)-A(J))
960 NN=(EPHIT-EXP(-ALPHA(J)*X))/(PHI(J)-ALPHA(J))
970 PCALC(2*I,J)=((M(J)/PHI(J))*(1-EPHIT)+LL*(MM+NN)+V(J)*PINIT(J)*EPHIT)/V(J)
980 GOTO 1000
990 PCALC(2*I,J)=-99
1000 RETURN
1010 PRINT"I=";I;"J=";J;"PCALC(2*I,J)=";PCALC(2*I,J);"M(J)=";M(J);"PINIT(J)=";PINIT(J):RETURN
```

Sample output, using Notigi reservoir data.

Reservoir:	1	2	3
V:	4.1E+09	4.1E+09	4.1E+09
M:	7E+10	7E+10	7E+10
Phi:	.6	.6	.6
a:	1	1	1
Alpha:	.8	.8	.8
B:	6.2E+11	6.2E+11	6.2E+11
T:	0	0	0

Year	PCALC(1)	PCALC(2)	PCALC(3)
0	30.000	30.000	30.000
1	63.390	96.004	127.861
2	90.800	149.413	205.917
3	92.317	151.957	209.032
4	80.594	128.820	174.788
5	66.136	100.504	133.191
6	53.719	76.250	97.653
7	44.568	58.397	71.524
8	38.377	46.326	53.869
9	34.411	38.595	42.565
10	31.962	33.824	35.589

Press any numeric key to continue. ?

APPENDIX 3

CALCULATION OF ϕ FOR SOUTHERN INDIAN LAKE
USING THE METHOD OF GRIMARD AND JONES (1982)

Appendix 3. Calculation of ϕ for Southern Indian Lake (before impoundment) using the method of Grimard and Jones (1982).

The equation of Dillon and Rigler (1974) was used to calculate the steady-state P concentration: $[P] = L(1-R)\cdot\bar{z}^{-1}\cdot\rho^{-1}$. The P loading (L) in $mg\cdot m^{-2}\cdot yr^{-1}$ was calculated as the total P loading to the lake (8×10^{11} $mg\cdot yr^{-1}$) divided by the area of the lake (2×10^{9} m^2; Newbury et al. 1984). R, the retention coefficient, was calculated using the equation of Kirchner and Dillon (1975), $R = 0.426 \exp(-0.271\cdot q) + 0.574 \exp(-0.00949\cdot q)$, or the simpler equation $R = 13.2\cdot(13.2 + q)^{-1}$ (Dillon, pers. comm. in Hough et al. 1980). The simpler equation was used here. The areal hydraulic loading (q) was calculated as $q = Q\cdot A^{-1}$ where outflow (Q) was 3.2×10^{11} $m^3\cdot yr^{-1}$ and lake area (A) was 2×10^{9} m^2 (Newbury et al. 1984). Mean depth ($\bar{z}$) was 8.5 m, and flushing rate (ρ) was 2 yr^{-1} (Newbury et al. 1984). The steady-state P concentration was 4×10^{2} $mg\cdot m^{-2}\cdot yr^{-1}(1-0.45)\cdot 0.12 m^{-1}\cdot 0.5$ yr $= 13$ $mg\cdot m^{-3}$ ($\mu g\cdot L^{-1}$).

APPENDIX 4

SOUTHERN INDIAN LAKE, NOTIGI AND WUSKWATIM
PREDICTED P CONCENTRATIONS

Appendix 4. Southern Indian Lake (reservoir 1), Notigi (reservoir 2), and Wuskwatim (reservoir 3) predicted P concentrations. Data entered are given in Tables 1, 2, and 3.
Note: printed parameter values are not necessarily the entered values because the program prints the last value used.

Reservoir:	1	2	3
V:	2.3E+10	4.1E+09	3.8E+09
M:	8E+11	7E+10	1.4E+11
Phi:	1.4	6.8	8.399999
a:	9	1	1
Alpha:	.8	.8	.8
B:	6.3E+11	6.2E+11	4E+11
T:	2	0	6

Year	PCALC(1)	PCALC(2)	PCALC(3)
0	25.000	30.000	35.000
1	25.000	63.390	40.259
2	25.000	90.800	44.576
3	34.066	39.154	39.891
4	31.683	34.568	35.162
5	28.582	30.135	30.440
6	26.688	27.517	38.523
7	25.713	26.171	31.172
8	25.245	25.519	29.920
9	25.027	25.213	27.998
10	24.927	25.071	26.635

Press any numeric key to continue. ?